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CHRONOLOGY AND ANALYSIS OF THE DEVELOPMENT OF ALTITUDE PERFORMANCE AND MECHANICAL CHARACTERISTICS OF A TURBOFAN ENGINE AT THE ARNOLD ENGINEERING DEVELOPMENT CENTER

ENGINE TEST FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE 37389

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Prepared for

ARNOLD ENGINEERING DEVELOPMENT CENTER (XO)
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE 37389

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FOR THE COMMANDER

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The chronology and analysis of the altitude development cycle of a typical current state-of-the-art turbine engine at the Engine Test Facility of the Arnold Engineering Development Center is reviewed to provide visibility and guidelines to improve the ETF/AEDC support capability to turbine engine test programs. A critical review of the program is reported with respect to three salient areas: (1) a comparison of the original test schedule with the achieved schedule, (2) a chronology of the engine builds tested,

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20. ABSTRACT (Continued)

(3) and a résumé of the test planning/coordination activities of the program.

PREFACE

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 65807F. The results presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee. The work was done under ARO Project No. R43Y-08A. The authors of this report were Jack T. Tate and T. J. Gillard, ARO, Inc. The manuscript (ARO Control No. ARO-ETF-TR-75-70), was submitted for publication on June 4, 1975.

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1.0 INTRODUCTION

The Engine Test Facility (ETF) at the Arnold Engineering Development Center provides the Air Force with an independent and objective turbine engine testing capability. Normalized testing techniques in terms of test equipment, instrumentation, test procedures, and analysis expertise are available for the evaluation of turbine engine functional and operating characteristics during any phase of an engine life cycle (Refs. 1 and 2). Air Force test requirements range from programs to investigate specific operational problems with in-service engines to programs designed to evaluate the basic operating characteristics of advanced technology prototype engine configurations.

To successfully accomplish the basic mission of the facility, a critique of all test programs is required to ensure that a continuing effort is made to maintain an efficient and responsive testing capability for all Air Force engines including the most current state-of-the-art configurations. Reported herein is a study of the altitude development testing accomplished on a typical state-of-the-art turbine engine at the ETF from the initial engine development phase (IED) through the altitude qualification phase (QT). The objective of the study is to provide a history of lessons learned and to make visible the activities, from a test facility viewpoint, which are efficiently accomplished and the activities which result in time, cost or quality penalties.

An objective review of the selected program is presented with respect to the test schedule, the chronology of the engine builds, and an assessment of the program planning and support activities. In addition, the general testing requirements for turbine engine development are discussed to provide a brief introduction to basic altitude test requirements.

2.0 TURBINE ENGINE DEVELOPMENT

2.1 GENERAL REQUIREMENTS

Turbine engine development is an empirical and iterative process. Testing of many configurations is required prior to the establishment of a production configuration with satisfactory stability, performance, reliability, and durability characteristics consistent with the propulsion system design operating envelope (altitude, Mach number, power range, flight maneuver limits, etc.). Extensive sea-level-static and ground environmental testing at simulated altitude conditions is required prior to the release of an engine for full production and operational use.

The USAF Scientific Advisory Board Report of the Ad Hoc Committee on Engine Development (Ref. 3) reports that: "During the development cycle a new engine typically

requires some 35 'builds' and four years before the engine is safe for first flight testing, then another 20 builds and one to two years before the engine can pass its military qualification test (MQT) and be certified for production. Experience indicates, however, that beyond this point another year (at a minimum) is required for testing of the engine/air frame combination throughout the expected operational envelope before the engine's 'bugs' are removed and the final weapon system is ready for production."

The initial phase of engine testing is generally accomplished at the manufacturer's sea-level test facilities to obtain parametric data and to establish a baseline for a demonstrator or prototype engine configuration and control system.

Altitude testing is initiated soon after the prototype configuration is established to determine the response of the configuration design to the primary environmental factors of the flight envelope (Reynolds number, temperature, ram ratio, and density effects). A listing of the primary altitude test requirements for development of a state-of-the-art supersonic, augmented turbofan, multimission turbine engine design is presented in Table 1.

Table 1. Turbine Engine Development Cycle Test Objectives

- **INITIAL ENGINE DEVELOPMENT**
  - **DEMONSTRATE PERFORMANCE AND STABILITY POTENTIAL**
    - **ENGINE AND COMPONENT PERFORMANCE**
    - **ENGINE STABILITY**
- **PRELIMINARY ENGINE DEVELOPMENT**
  - **DEVELOP FLIGHT SUITABILITY CHARACTERISTICS**
    - **STRUCTURAL CHARACTERISTICS**
    - **RELIABILITY CHARACTERISTICS**
    - **ENGINE STABILITY**
    - **ENGINE AND COMPONENT PERFORMANCE**
- **ADVANCED ENGINE DEVELOPMENT**
  - **DEVELOP OPERATIONAL SYSTEM CAPABILITY**
    - **ENGINE AND COMPONENT PERFORMANCE**
    - **ENGINE STABILITY**
    - **ENGINE RELIABILITY**
    - **ENGINE DURABILITY**
    - **ESTABLISH ENGINE QUALITY AND ENVELOPE LIMITS**

Testing in both sea-level and altitude ground test facilities continues in the iterative development cycle process to establish an engine configuration suitable, first for flight testing, and finally for production and operational use.

2.2 ALTITUDE TEST REQUIREMENTS

Altitude testing in ground test facilities is an essential element in the development cycle of current high performance aircraft turbine engines. As engines have become more complex to satisfy increased performance and multimission requirements of modern aircraft systems, the need for simulated flight testing has increased.

The requirement for flight testing is readily apparent; the final authentication of acceptable engine and propulsion system operation is the successful demonstration of engine performance when integrated with the airframe in flight. Flight testing, however, is a high risk (in terms of cost and time) test technique. Altitude testing in ground test facilities is required for engine development within the lead time and cost limits of new and advanced engine systems.

Recent turbine engine development trends have departed from the policies of a decade ago when there was a steady stream of aircraft turbine engine developments with the main trend toward "bigger-faster-higher" systems (Refs. 4 and 5). Pinkel and Nelson report in Ref. 4 that: "In a large number of cases the engine originally developed for a given airplane proved inadequate, and the airplane ultimately employed a different and usually higher thrust engine in its operational version. Since 1960, the number of engine developments has greatly decreased. Because of this and because of the greater specialization of engine design to meet the greater number of special requirements imposed on current aircraft, the fate of an airplane is much more dependent on the adequacy and availability of the engine developed for it."

The development schedules and costs of current aircraft systems make it increasingly important that a compatible engine system is developed prior to first flight. Major engine design modifications, in response to problems discovered during flight test, can result in severe time, cost, and/or performance penalties.

The fundamental test requirement of the altitude development cycle is to provide a quantitative data base for (a) the assessment of the performance, stability, reliability, and durability characteristics of the engine, and (b) the required technical visibility for timely and responsive management decisions by the customer - engine company - aircraft company team. A building block concept, using normalized test techniques and procedures with standardized nomenclature and communication methods, is essential to evaluate the technical risk and cost trades during system development. Time-phased assessments to verify predictions and estimates at milestone points in the schedule are required to avoid technical surprises and provide a meaningful data base for management decisions.

3.0 TEST SCHEDULE

3.1 INTRODUCTION

Schedule considerations have a major impact on the resources required and the development test plan of a new engine system. The test schedule indicates the milestone requirements to achieve system development by a required calendar date. The importance of establishing a realistic test schedule is readily evident. New engines which extend the technology are, by necessity, high risk designs; development schedules based on unrealistic success criteria can, and often do, result in costly delays in initiating engine production and/or in decisions to shorten the required development testing to "maintain the schedule."

Shortened development test schedules, which reduce the time and cost of "seemingly expensive" development tests often appear attractive to program managers. However, "a study of modern engine development experience indicates that most of our difficulties have come through attempts to shorten the development cycle to fit a politically or financially dictated program (Ref. 3). Shortened development schedules can often result in "panic" test programs to provide "fixes" for the production configurations to keep the force operational. A careful analysis of the risks of shortened development schedules which reduce testing requirements should be made at all decision points. The expense of accelerated development testing (additional engine builds, increased testing rates, etc.) may be relatively low compared with the cost of production schedule delays and/or grounded aircraft.

3.2 GENERAL OBJECTIVES

The basic test objectives of a typical turbine engine development cycle are shown in Table 1. Three phases of the development cycle are identified. The first phase is defined as the Initial Engine Development (IED) and is required to demonstrate the performance and stability potential of the prototype configuration. The second phase is defined as Preliminary Engine Development and includes the development testing required to establish a Preliminary Flight Rating Test (PFRT) engine configuration suitable for flight test operations. The third phase, identified as the Advanced Engine Development, completes the development cycle with Qualification Testing (QT) to authorize initial engine production. As indicated in Table 1, the test objective of the first phase is to demonstrate the potential of the configuration. The test objectives of Preliminary Development are to develope flight safety and suitability (structural, reliability, stability, and performance characteristics) for limited flight envelope operation. The test objectives of Advanced Engine Development are to develope the engine performance, suitability, reliability, and durability characteristics to the design goals.

3.3 TYPICAL TEST PROGRAM SCHEDULE

The test schedule established for the typical engine development program reported herein is presented in Fig. 1. The three phases of the program were scheduled to be completed in 39 months; however, the actual testing required an additional 9 months because of extended time requirements for the preliminary development phase (~6 months), and, to a lesser extent, the advance development phase (~3 months). However, the extended calendar time requirement in this case is not attributed to increased testing because of engine development difficulties or operational problems, but to delays in testing progress because of the limited availability of test hardware (engines). The estimated engine operating time and engine builds for the altitude development program are shown in Fig. 2. The engine operating time accumulated, which is indicative of engine development program progress is, as expected, almost directly related to the availability of engine test hardware. Approximately 2,000 engine hours and 15 engine builds were estimated to be required to accomplish the scheduled 39-month altitude development program. The actual requirements were approximately 1,800 engine hours (and 14 engine builds) and 48 months. A significant schedule delay was experienced because of delays in engine hardware delivery early in the program. Some recovery in the schedule was obtained during the latter phases of the program by rescheduling additional test units and work shifts to accelerate testing. Three, rather than the scheduled two test cells, were required to avoid severe schedule delays (Fig. 3).

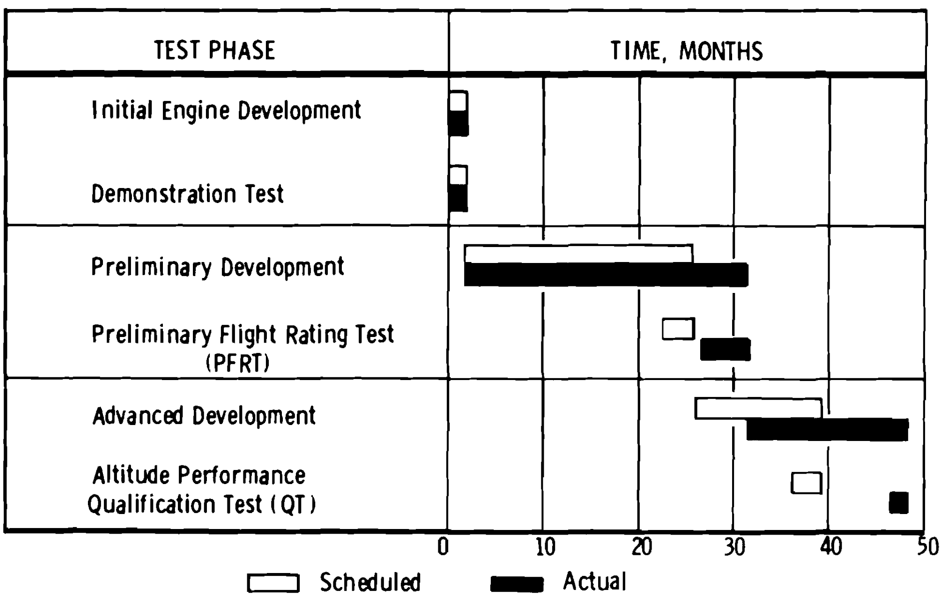


Figure 1. Turbine engine altitude development program schedule.

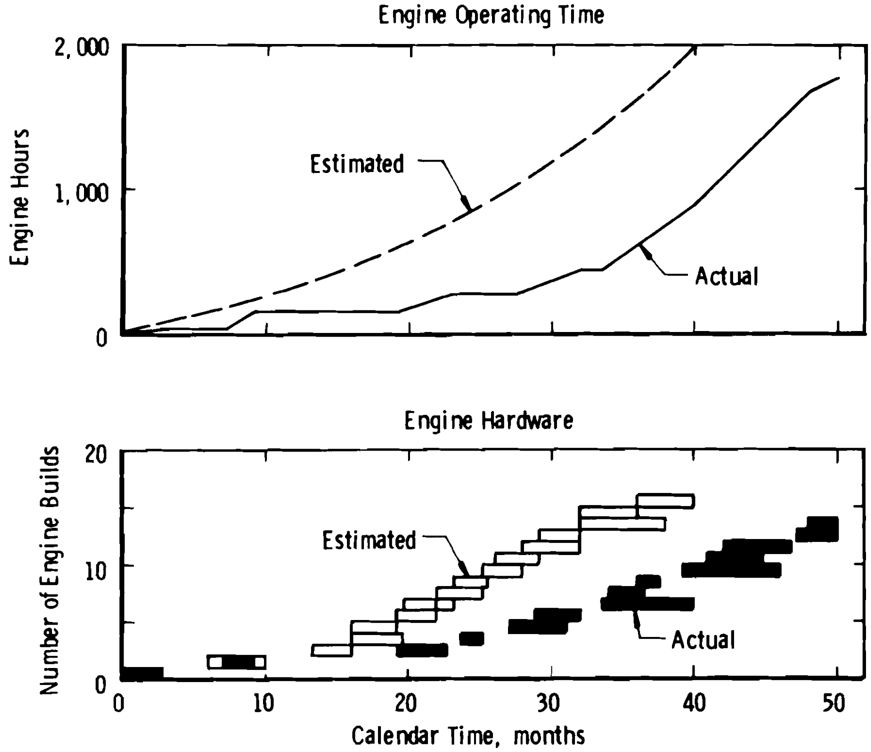


Figure 2. Engine test requirements for an altitude test program.

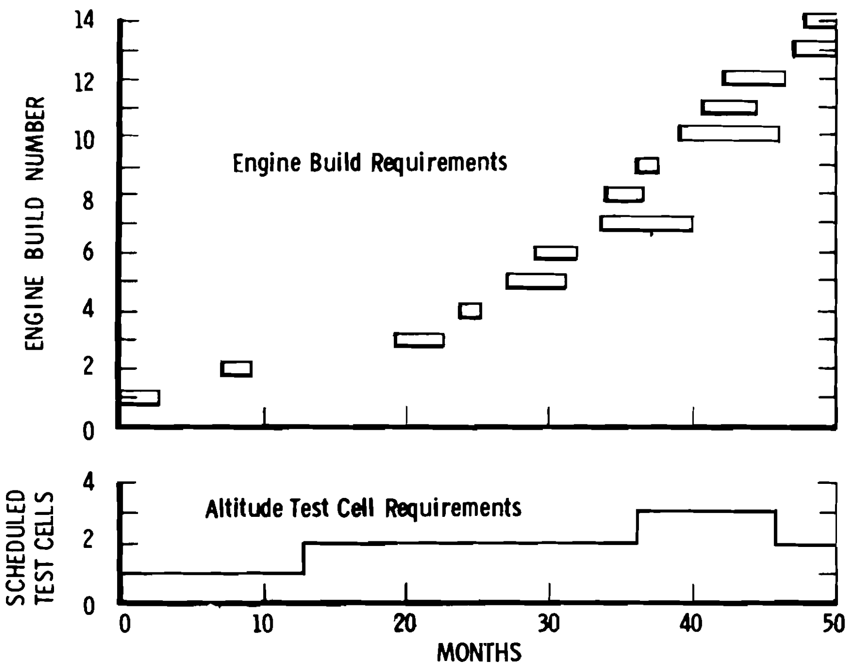


Figure 3. Test cell requirements.

Estimated altitude development program schedules are dependent on engine hardware and test facility availability. Because of the low maturity level of engines in the early stages of development, a relatively low testing rate and high maintenance level must be anticipated. Significant overall program delays can result from the unexpected "loss" of a single-engine build early in the test program, whereas the "loss" of an engine build late in the program will have a lesser impact on the overall test schedule. Hence, careful planning of the test hardware requirements is neccessary early in the development cycle to achieve a cost effective balance with proper consideration for schedule risks and the relatively high costs of early prototype engine builds.

However, test program progress and engine hours are not solely dependent on test hardware availability. Many considerations, such as the engine functional test requirements, the development status of major components, the environmental test requirements, etc., which are required for test program progress, are all major influences in the testing rate of the program. These factors are discussed in the following sections.

4.0 CHRONOLOGY OF ENGINE BUILDS

4.1 INTRODUCTION

A history of the engine builds utilized during the selected program is presented to indicate the typical testing trends for an altitude development program. The chronology of engine builds includes the following:

1. The general classification of the development status of the major components in each build.
2. The total engine hours accumulated on each engine build and engine hours utilized in evaluating each major test objective.
3. Significant operating experience and engine difficulties encountered with each engine build.
4. The performance of major engine components as a percentage of specification for each engine build.

4.2 DEVELOPMENT STATUS OF ENGINE HARDWARE COMPONENTS

The general classification of the development status of the major components of each engine build is presented in Table 2. The general trend in growth from the IED engine configuration to the QT engine configuration may be noted. The PFRT and QT

Table 2. Development Status of Major Components

Component	Engine Build													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Fan	IED	Pre-PFRT	Pre-PFRT	PFRT	PFRT	PFRT	Pre-QT	PFRT	Pre-QT	QT	PFRT	Pre-QT	QT	QT
High-Pressure Compressor										Pre-QT				
Combustor														
High-Pressure Turbine		PFRT	PFRT			Pre-QT								
Low-Pressure Turbine		Pre-PFRT	Pre-PFRT			Pre-QT								
Augmenter		Pre-PFRT	Pre-PFRT			PFRT								
Nozzle		PFRT	PFRT	Pre-QT	Pre-QT					QT				
Control System	Non-Integral	Non-Integral	Pre-PFRT Integrated	PFRT Integrated	PFRT					Pre-QT	Pre-QT			

configurations are specific designs established for model qualification testing. The pre-PFRT, pre-QT, and other nomenclature indicates any of the several candidate configurations evaluated during the altitude development cycle. Logistic considerations during the development program often require the use of obsolete component designs to maintain engine build schedules when these components have no major impact on the primary test objectives planned for the builds.

4.3 TESTING EXPERIENCE

The total engine hours accumulated with each engine build is presented in Fig. 4. The engine power spectrum is also indicated in terms of engine hours at intermediate

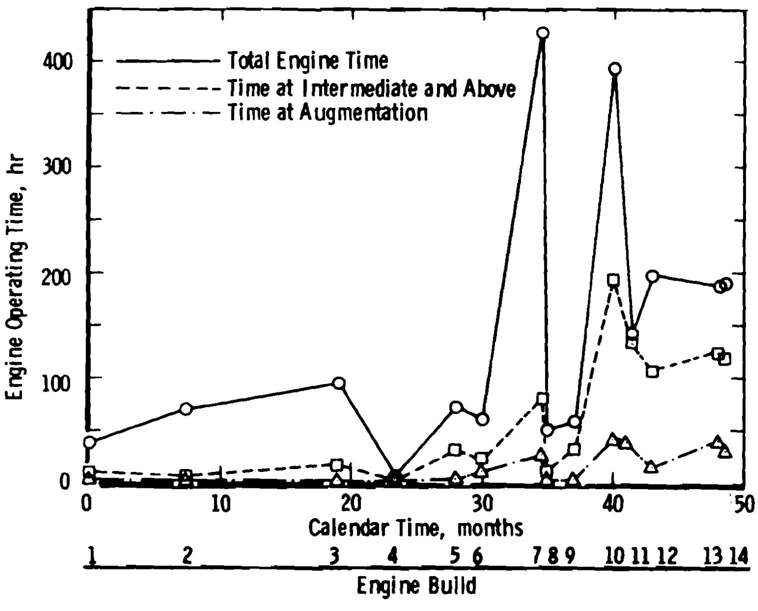


Figure 4. Engine operating time as a function of engine build and calendar time.

and higher power conditions and hours at augmented power. Engine hours in terms of the test objectives of each engine build are presented in Table 3. The general increase of engine hours as a function of engine build and development time is readily apparent. Fewer than 100 engine hours were obtained with each of the first six engine builds (first 32 months of testing). Well over 100 engine hours (140 to 430) were obtained on all but two of the last eight engine builds tested. The capability and requirement to operate at higher engine power also increased as the development program progressed. Baseline engine operating characteristics were the primary test objectives through PFRT testing (build 5). Increased emphasis on controls development and high engine power (afterburning) performance was required during advanced engine development (builds 6 through 14).

Table 3. Detail Test Objective
a. Initial Engine Development

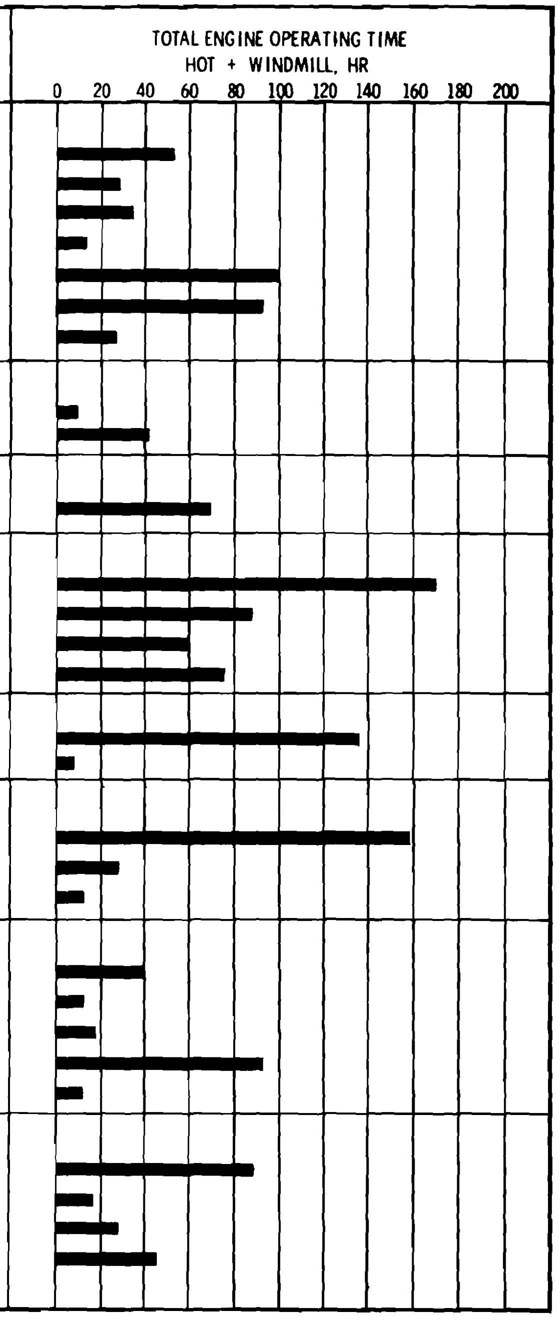
ENGINE BUILD	TEST OBJECTIVE	TOTAL ENGINE OPERATING TIME HOT + WINDMILL, HR 0 20 40 60 80 100 120 140 160 180 200
No. 1	1. Engine and Component Performance 2. Inlet Distortion Effects on Engine Stability	

b. Preliminary Engine Development

ENGINE BUILD	TEST OBJECTIVE	TOTAL ENGINE OPERATING TIME HOT + WINDMILL, HR
No. 2	Development Pre-PFRT 1. Engine Performance 2. Windmill Speed Characteristics 3. Windmill Start Characteristics 4. RN Effect on Performance 5. Inlet Distortion Effects on Stability	
No. 3	Development Pre-PFRT 1. Windmill Start Characteristics 2. Windmill Speed Characteristics 3. Lube System Heat Rejection 4. Engine and Component Performance 5. Effects of Customer Bleed on Performance	
No. 4	Development Pre-PFRT 1. Stability Verification with Inlet Simulator	
No. 5	Preliminary Flight Rating Test 1. Engine Performance 2. Inlet Distortion Effects on Engine Stability 3. Control Schedule Development	
No. 6	Development Pre-QT 1. Flight Test Support Stability Characteristics	

Table 3. Concluded
c. Advanced Engine Development

ENGINE BUILD	TEST OBJECTIVE	TOTAL ENGINE OPERATING TIME HOT + WINDMILL, HR (0 20 40 60 80 100 120 140 160 180 200)
No. 7	Development Pre-QT 1. Engine Performance 2. Windmill Starting Characteristics 3. Windmill Starting Capability 4. Augmenter Development 5. Nozzle Development 6. Control Schedule Development 7. High Q Functional Test	
No. 8	Development Pre-QT 1. High Q Turbine Endurance Testing 2. Stability Testing	
No. 9	Development Pre-QT 1. Trim Curve Development	
No. 10	Development Pre-QT 1. Engine Performance 2. Augmenter Development 3. Fan Performance and Stability 4. Controls Schedule Development	
No. 11	Development Pre-QT 1. Augmenter Functional Characteristics 2. Flight Test Support	
No. 12	Development Pre-QT 1. Augmenter Operational Characteristics 2. Fan Development 3. Engine Spooldown Relight Capability	
No. 13	Development Pre-QT 1. Functional Test (ET&E) 2. Humidity Effects on Performance 3. Nozzle and Augmenter Development (CIP) 4. Fan Core Splitter Evaluation (CIP) 5. Trim Curve Evaluation (CIP)	
No. 14	Qualification Test 1. Engine Performance (QT) 2. Controls Schedule Definition (Flight Support) 3. Augmenter Development (CIP) 4. Effect of Bleed & HP (ET&E)	



A typical turbine engine operating envelope with the engine operating limit regions noted is shown in Fig. 5a. The engine hours accumulated as a function of the engine operating envelope and calendar time is presented in Fig. 5b. Testing early in the program was generally limited to the relatively favorable engine operating conditions of the central

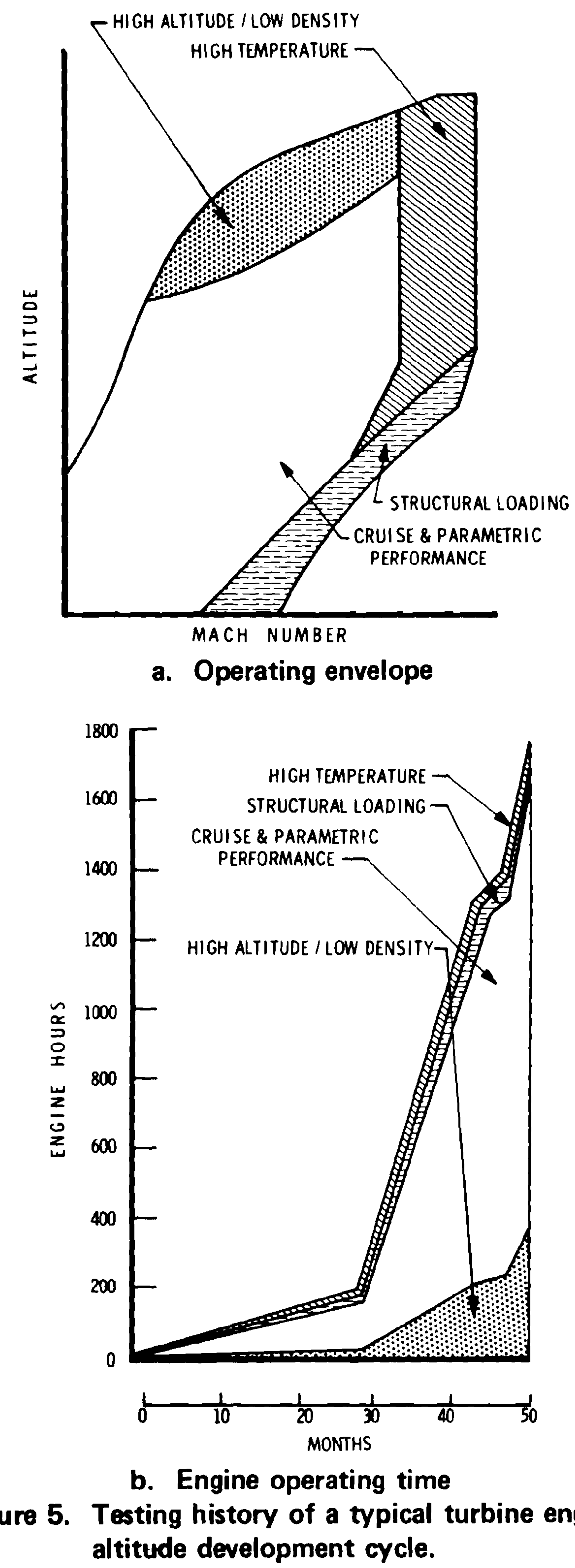


Figure 5. Testing history of a typical turbine engine altitude development cycle.

portion of the envelope for the baseline performance and parametric investigations. Engine operation in the envelop limit regions was investigated to a greater extent as testing advanced with succeeding builds and increased engine maturity.

4.4 OPERATING EXPERIENCE

The significant operating experience and engine difficulties encountered with each engine build are discussed in terms of engine durability incidents and engine reliability incidents. Engine durability characteristics are defined as the engine characteristics which determine the operating life or structural limits of the engine configuration/build. Typical examples of durability incidents include compressor/turbine blade failure, bearing or bearing seal failure, engine/component case ruptures, fuel or lubrication system cracks and/or pump malfunctions, burned combustors and afterburner components, and exhaust nozzle structural failures.

Engine reliability characteristics are defined as engine characteristics which determine the functional adequacy of the engine. Typical examples of reliability incidents include control system malfunctions, sensor limitations, variable geometry instabilities, main combustor and afterburner instability, and compression system instability.

The incident rates experienced as a function of engine build are shown in Fig. 6. "Scheduled" or "expected" incidents, such as high altitude afterburner blowout or burning

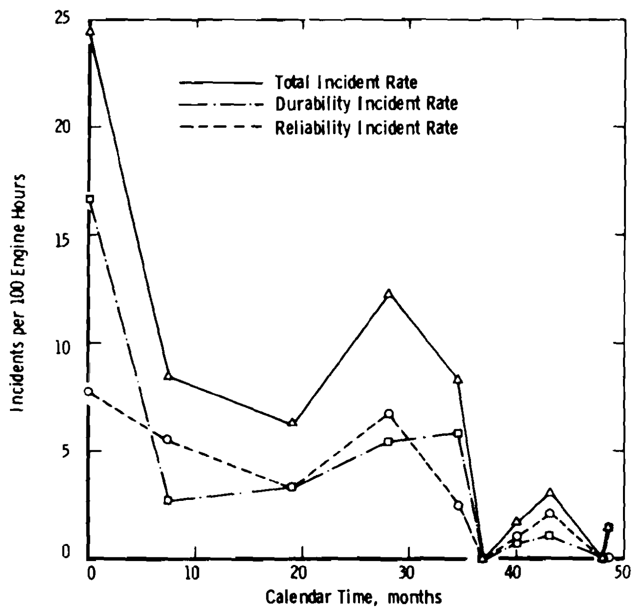


Figure 6. Durability and reliability incident rate variation with calendar time.

instability experienced during testing designed to define the operating altitude limit, were not included; the data presented contain only incidents which resulted in unscheduled testing delays or test plan deviations.

The expected trend of increased engine reliability/durability occurred as the engine configuration matured. The periodic variations in the general trend are attributed to the increased severity of the test conditions (increased high power engine operation and increased operation in the limit regions of the engine envelope) imposed on the engine as it matures.

The incident frequency as a function of major component is presented in Fig. 7. For the typical engine system reported herein, control system reliability incidents were responsible for over 30 percent of the total number of incidents reported. The high incident rate is attributed to the increased complexity of current state-of-the-art turbine engine control system; control of state-of-the-art engines requires up to 7 degrees of freedom, whereas control of engines in the 1950's required only 2 or 3 degrees of freedom.

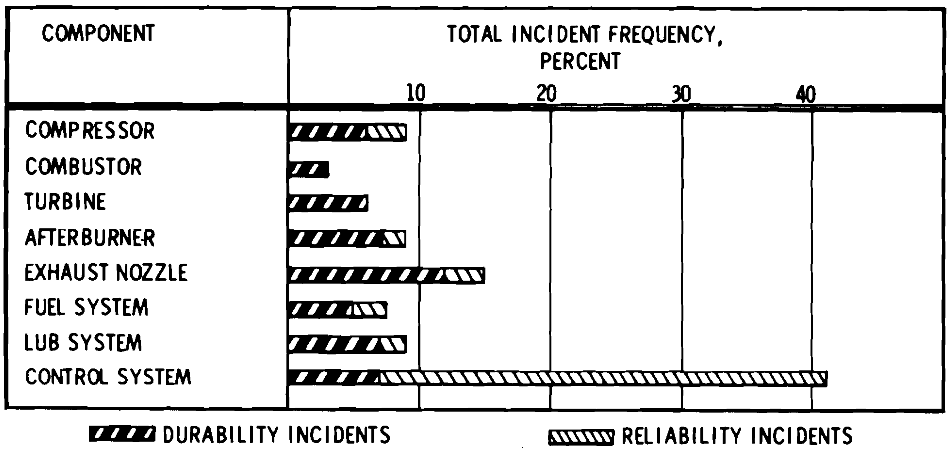


Figure 7. Durability and reliability incident frequency as a function of major engine component.

4.5 ENGINE PERFORMANCE

Engine development programs are tracked in terms of performance, durability, and reliability characteristics. The primary requirement of an altitude qualification test is an assessment of engine performance at specified test conditions (engine power level and trim conditions, altitude, Mach number, inlet ram recovery, etc.).

The number of specification conditions is based on the projected mission profiles of the aircraft system and is selected to cover the critical regions of engine operation

such as takeoff performance, cruise conditions (where fuel consumption is most important), and dash conditions (where high engine thrust is the primary parameter).

Engine performance data at the specification conditions are not obtained for all engine builds during the engine development cycle. The detailed test objectives necessarily vary with each engine build, and overall engine performance is not always a primary test objective for each engine build, as indicated in Table 3.

However, some insight into engine performance development, as a function of calendar time and engine build, may be obtained by tracking component and overall performance relative to specification math model estimates at selected critical regions and power levels within the engine flight envelope. An engine math model is a mathematical definition of the engine cycle characteristic based on the manufacturer's design experience and component test data and may be used to provide estimates of engine performance at any requested flight and power level condition. The specification math model is the engine manufacturer's estimate of the performance characteristics of the engine at the completion of the development cycle (engine qualification). Use of the specification math model estimates provides the capability for valid engine-to-engine comparisons; minor variations in flight condition or engine power are generalized by using the math model as a reference.

The engine performance development history of the program discussed herein was assessed at three engine operating conditions of interest relative to a typical mission duty cycle. The selected conditions are shown in Fig. 8. Intermediate engine power at sea-level-static conditions was selected to track baseline engine trim performance; part-power engine operation at subsonic cruise Mach number conditions was selected to provide an assessment of the "mileage" or cruise performance capability of the engine, and maximum augmented power engine operation at high Mach number flight conditions was selected to provide a condition where maximum thrust capability is most significant.

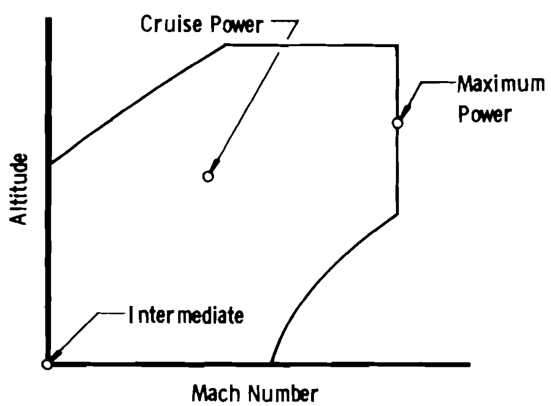
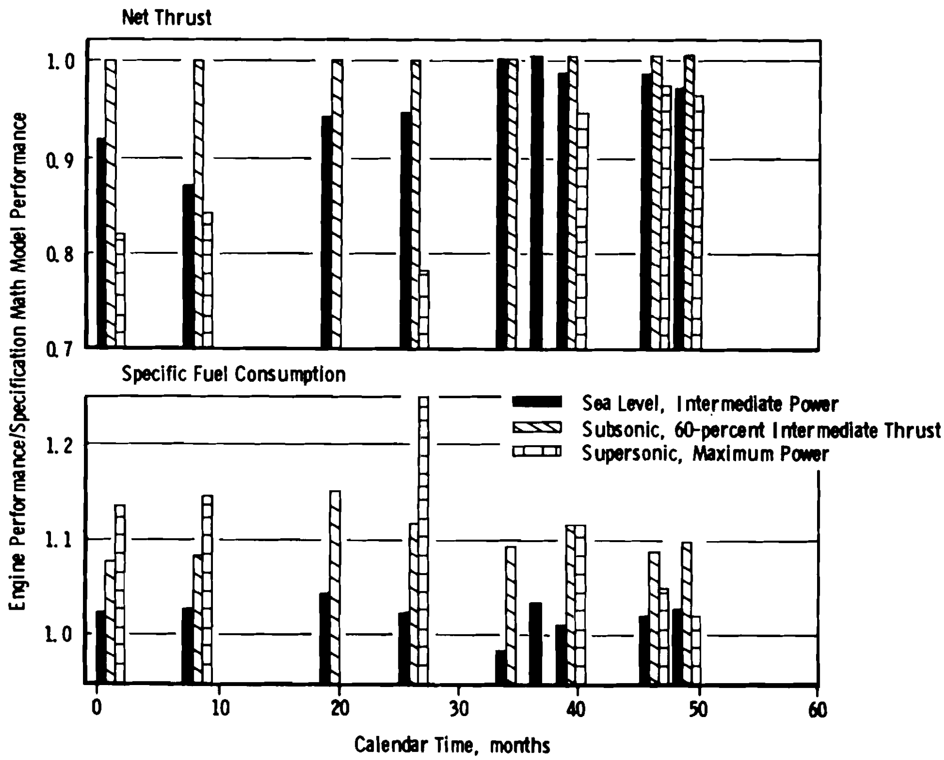


Figure 8. Engine performance evaluation conditions.

Overall and component performance data relative to specification math model values at the three selected conditions are shown in Fig. 9 as a function of calendar time. Net thrust and specific fuel consumption performance are presented in Fig. 9a. Fan, high-pressure compressor, and turbine component performance are presented in Figs. 9b, c, and d, respectively. Augmenter and nozzle performance are shown in Fig. 9e.

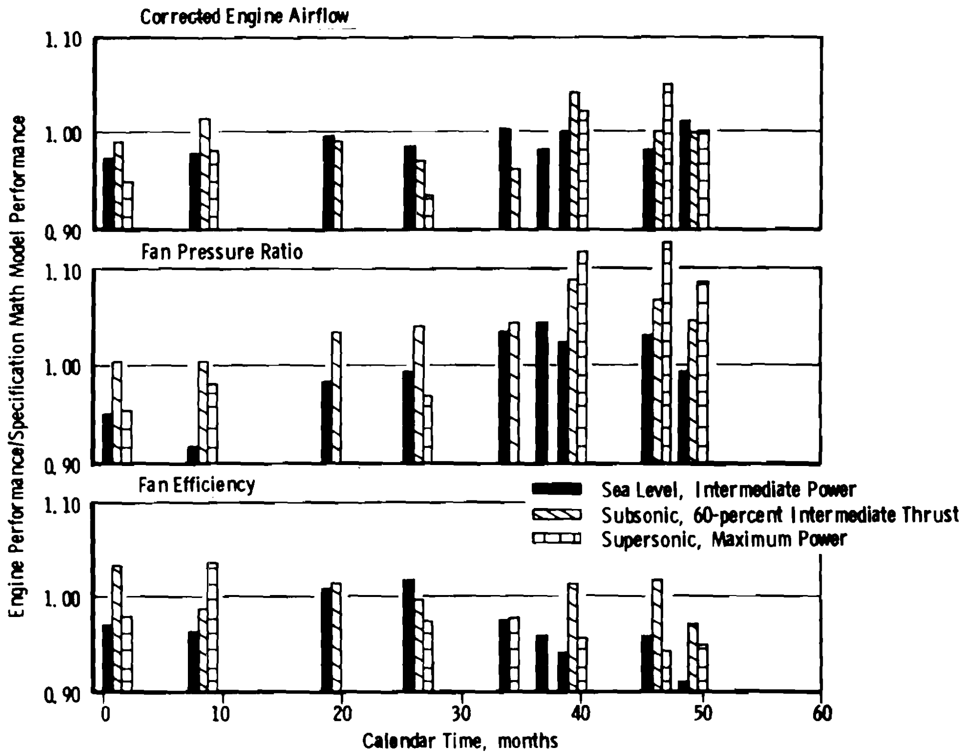
At intermediate power, sea-level-static conditions, engine thrust increased from about 92 percent of the specification deck estimate at IED to over 98 percent with the QT configuration engine without a significant variation in specific fuel consumption or engine (fan) airflow (Figs. 9a and b). Engine airflow, which is significant because of inlet-engine matching considerations, and thrust specific fuel consumption for the QT engine configuration were within 2 percent of the specification values. However, turbine inlet temperature, which is an important engine durability consideration, was approximately 7 percent greater than the specification estimate. The higher-than-estimated temperature level is indicative of an engine life-for-performance trade decision.

Specific fuel consumption performance is a primary parameter of interest in the evaluation of engine cruise performance. The specific fuel consumption demonstrated with the IED prototype engine configuration at cruise conditions (Fig. 9a) was maintained with the QT engine configuration; however, specific fuel consumption was approximately 8 percent higher than the specification requirement. The inability to obtain the estimated QT performance is attributed to the slightly lower-than-estimated performance of all major engine components (Figs. 9b through e) rather than to a specific performance problem with any of the major engine components.

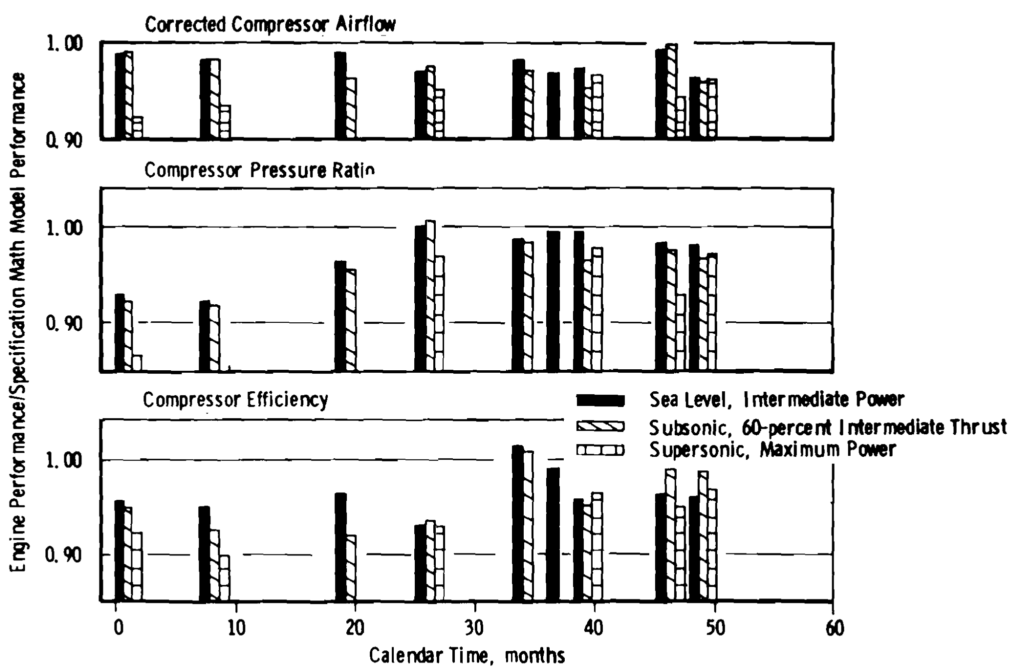


a. Overall performance

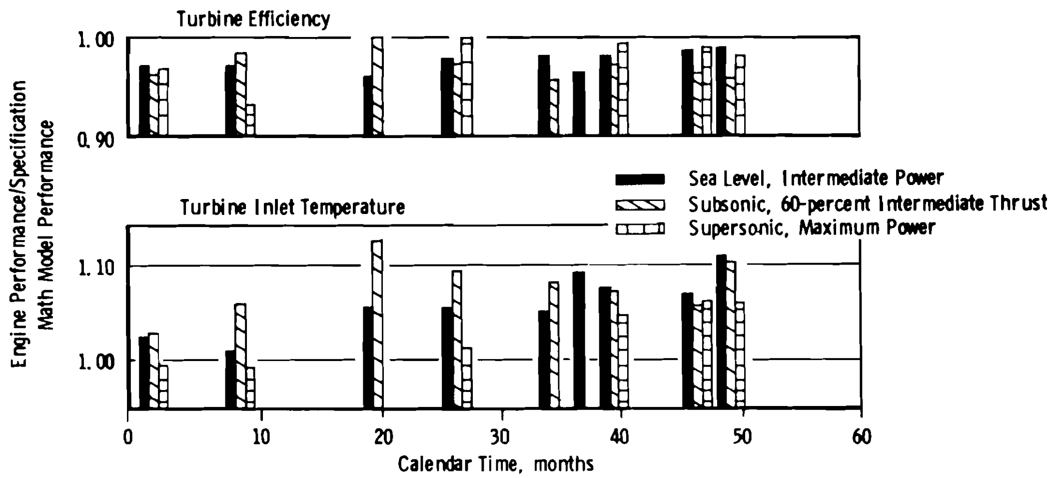
Figure 9. Engine performance as a function of calendar time.



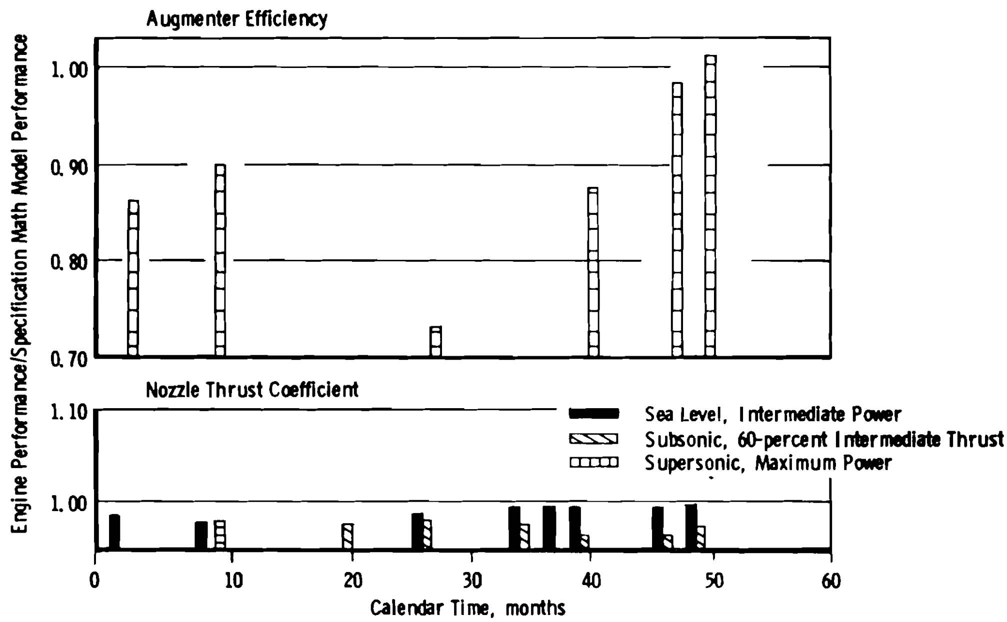
b. Fan performance



c. High-pressure compressor performance
Figure 9. Continued.



d. Turbine performance



e. Augmented and nozzle performance
Figure 9. Concluded.

Thrust performance is a primary parameter in the evaluation of the supersonic flight condition engine performance. With the IED engine configuration, only about 80 percent of the specification math model maximum thrust performance was obtained, and specific fuel consumption at maximum thrust was significantly higher (13 percent) than the specified math model value. Maximum thrust performance increased significantly with the

engine builds tested during the latter part of the program, and thrust performance was approximately 98 percent of the specification value for the QT configuration engine. The significant thrust performance increase is attributed to the increase in augmenter efficiency (Fig. 9e) as engine development progressed.

The performance of the major engine components, at the three engine test conditions identified herein, is shown in Figs. 9b through e. Compression system efficiencies (Figs. 9b and c) of the QT engine configuration were generally between 95 and 100 percent of the estimated value. Fan pressure ratio was increased during the development cycle and ranged between 100 and 114 percent of the estimated value with the QT configuration engine. Operation at the higher fan pressure ratio is indicative of a fan performance-stability trade decision during the engine development cycle.

Tubine efficiency did not vary significantly during the development cycle. However, turbine inlet temperature increased to values ranging between 105 and 110 percent of the estimated values for the QT configuration. The increased temperature indicates a performance-durability trade decision.

The performance-stability-life (durability) trade decisions required during development testing illustrates the empirical and iterative process which is typical of an engine development cycle. The timely development of a production engine configuration with satisfactory characteristics throughout the operating envelope of the propulsion system requires a well planned and executed test program to provide the required time phased test results from many engine configurations.

5.0 TEST PROGRAM COORDINATION

5.1 BASIC REQUIREMENTS

Essentially all detailed test planning for an altitude test program must be accomplished prior to the initial phases of the engine development cycle and the establishment of the engine development milestone schedule. The quality of the data bank established during the engine development program is a direct function of the detailed test program planning and coordination efforts between the customer, engine company, aircraft company, and testing facility.

Normalized definitions, nomenclature, instrumentation procedures, testing techniques, data acquisition and processing methods, and engine assessment formats are essential for effective program management. A high degree of standardization enhances the communications within the testing team. The detailed test planning should include the detailed engine performance and stability development plan, the required instrumentation and test hardware designs, and the data analysis software and computer model formulation.

Scheduling considerations should include clear definition of the availability of required information items such as engine operating and maintainence instructions/requirements, engine and test hardware configuration definitions, detailed instrumentation configuration and facility-engine interface definitions, data analysis/presentation/transmittal and information feedback plans, etc., as well as primary hardware (engine build) delivery data and required test program priorities. It is beyond the scope of this report to enumerate the many detailed planning/coordination activity items which were successfully accomplished. However, several noteworthy planning and coordinating procedures were adapted and are briefly discussed.

5.2 TEST PLANNING

Detailed test program planning for a multi-engine, complex test program is difficult because of the severe impact resulting from variations and interruptions in high-risk engine hardware delivery schedules during the initial phases of the development cycle. An effective test planning procedure, designed to provide a greater flexibility to the program effort, was the use of "mini-test plans." The mini-test plan procedure allowed the overall test program to be subdivided into relatively small-scope, objective-oriented testing efforts not related to specific engine builds. With the minimum test requirements (engine configuration, instrumentation, etc.) specified with each mini-program, productive testing with available engine hardware (builds) could be scheduled with minimum lead time. "Last-minute" execution of the mini-test plans could be accomplished with the benefit of in-depth and carefully coordinated test planning.

Full exploitation of the mini-test plan concept requires the normalization of engine instrumentation requirements. Although the detailed instrumentation requirements for each mini-program may necessarily change to some extent with the detailed program objectives, a high degree of normalization can be achieved if the detailed test program planning effort is disciplined to maintain consistent engine-to-engine instrumentation requirements throughout the test program.

5.3 DETAILED TEST COORDINATION

Effective communication techniques are required for detailed test coordination during the conduct of an altitude test program. The required level of communication and coordination for the program reported was obtained by recognition of, and response to, two basic test planning/coordination requirements:

1. On-site customer, engine manufacturer, and test facility representatives with decision-making authority, and

2. Regular (weekly) coordination meetings to review/discuss/communicate detailed test results, near-term test requirements, and long-range test plans.

These coordination efforts proved extremely effective in avoiding costly time delays awaiting test direction decisions and in maintaining a cross feed of vital information.

5.4 ENGINE CONTRACTOR TEST ARTICLE SUPPORT

Test engines generally require significant engine-contractor maintenance support during the initial phases of the development cycle. As the engine matures and operating and maintenance procedures are developed, less engine contractor maintenance is required. Contractor support for the program reported herein ranged from 10 to 20 on-site engineers and craftsmen during the initial phases of the program to 5 to 10 during the latter phases, depending on the number of test engines in operation and the complexity of the test programs. In general, the level of support provided was sufficient; testing delays attributed to insufficient on-site engine contractor test article support were not significant. However, as noted in Section 3.0, the delays of test hardware during the early phases of the altitude test program delayed the engine altitude development progress.

Engine development schedules must be maintained to avoid the prohibitive cost penalties resulting from delays in system production and deployment. Hence, from a major engine development program viewpoint, acceleration of the development cycle through the use of additional resources (altitude test facility manpower and test cells) is a reasonable and cost effective method to recover from development schedule delays. However, from a test facility viewpoint, significant rescheduling requirements can have a major impact on the test schedules of other planned programs and can have a significant effect on the efficiency of facility operations. Realistic engine development schedules with test hardware support visibility coupled with program milestones which provide "early warnings" of program schedule delays should be considered during facility schedule negotiations.

6.0 SUMMARY

A review of the chronology and analysis of the altitude development cycle of a typical current state-of-the-art turbine engine at the Engine Test Facility of the Arnold Engineering Development Center was conducted. A summary of the results of this review is presented as follows:

1. Test schedule progress is directly related to testing progress (engine hours) which is a function of the available test hardware (engine builds). Significant program delays can result from delays in the initial engine builds available

for the development program; although early prototype engine builds are relatively expensive, an additional engine build may be the most cost effective method available to reduce the risk of a high cost production delay.

2. Limited engine test time (generally less than 100 hr total operating time for each engine build) and limited operation in the engine envelope operating limit regions should be anticipated during preliminary development (prior to PFRT).

3. A relatively high rate of engine reliability and durability incidents which impact testing progress and/or detailed test schedules can be expected during the early phases of engine development. The incident rate during preliminary development (prior to PFRT) was approximately twice the incident rate during advanced development (after PFRT) for the typical test program evaluated.

4. The math model specification deck is an effective tool for tracking component and overall engine performance during the altitude development testing cycle. Differences in test conditions and engine power settings can be normalized to provide valid engine-to-engine comparisons.

5. The sophisticated and complex control systems of current state-of-the-art multimission turbine engines require significant testing to achieve an acceptable reliability status. For the typical turbine engine development cycle evaluated, control system reliability incidents accounted for over 30 percent of the total incidents reported.

6. Successful program management requires effective communication methods, detailed pretest planning, responsive test direction, and test program flexibility. Normalized definitions, nomenclature, instrumentation procedures, testing techniques, data acquisition and processing methods, and engine assessment formats must be established to achieve effective communications. The mini-test plan concept, which subdivides major test phases into relatively small-scope objective-oriented test efforts, provides test program flexibility with minimum impact on in-depth test planning. The maximum program flexibility capability can be provided when the test program planning effort is disciplined to maintain consistent, normalized engine-to-engine instrumentation requirements. On-site customer, engine-manufacturer, and test facility representatives with decision making authority provide responsive test direction.

REFERENCES

1. Tate, Jack T. and Smith, R. E., Jr. "Normalized Testing Techniques to Determine Turbine Engine Stability Margins." AEDC-TR-71-249 (AD907280L), January 1973.

2. Hood, P. M. "Capabilities for Turbine Engine Testing at the Arnold Engineering Development Center." ASME 71-WA/GT-8, August 2, 1971.

3. Scientific Advisory Board United States Air Force. "USAF Scientific Advisory Board Report of the Ad Hoc Committee on Engine Development." August 1973.

4. Pinkel, B. and Nelson, J. R. "A Critique of Turbine Engine Development Policy." Memorandum RM-6100/1-PR, April 1970.

5. Montgomery, J. Franklin, III. "The Need for Air Force Engine Stability Margin Testing for Inlet-Engine Interface Definition." AFAPL-TR-71-84, December 1971.